LLNL-TR-426235

Zero-Order Phased Fiber Arrays

M. J. Messerly

March 19, 2010

Technical Report

Auspices Statement

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was funded by the Laboratory Directed Research and Development Program at LLNL under project tracking code 0X-XX-XXX.

FY09 LDRD End-of-Project (Final) Report
Zero-Order Phased Fiber Arrays
LDRD Project Tracking Code: 08-LW-052
Michael J. Messerly, Principal Investigator

Abstract

Phased arrays remain an important strategy for scaling average power and pulse energy in optical fiber lasers. In zero-order arrays, the lengths of the constituent lasers or amplifiers are matched to within the coherence length of a pulse; for fibers having bandwidths on the order of one nanometer, lengths must be matched to 1 mm; for fiber having bandwidths on the order of 30 nm (pulse duration of 100 fs), lengths must be matched to 30 µm.

The overarching goal of this work has been to demonstrate a scaling path to 10 mJ pulses from an array of fiber lasers, with each fiber contributing roughly 1 mJ of energy. The near term goals were, and remain, two-fold. First, to demonstrate that arrays of fiber amplifier chains can be created having path length differences on the order of sub-picoseconds. This has been accomplished, showing that sub-nanojoule, 200 fs pulses can be split into an array of four chains, each chain amplified with a single preamp, and the outputs can be recombined within the coherence length of the pulses.

The second near term goal, stabilizing the phase through active feedback, is not yet complete. The strategy has been to generate an out-of-band CW seed signal that is monitored to account for fluctuations in path length that occur between pulses. At this point the necessary hardware is in place, but the control electronics are not.

We expect the co-phasing work to continue under separate funding, though in a simpler form. Instead of combining pulses from many amplifiers we would combine many sequential pulses from a single fiber laser via a resonant cavity. Such a scheme is less expensive to build and test (and eventually, to field), though significant technical hurdles must be overcome, including the development of a low-loss mechanism for releasing the energy that is built up within the cavity.

Introduction/Background

Three beam-combining techniques continue to dominate: active phasing, wavelength multiplexing, and passive combining.

Active phasing. In this technique, the relative phases of lasers in an array are monitored and adjusted via feedback loops to keep the lasers co-phased to within $2\pi/10 \pm 2m\pi$, where m is an integer. Proponents of this technique include researchers at the Air Force Research Laboratory [1] and MIT Lincoln Labs [2].

In current active phasing approaches, m is a large integer (typically greater than 10^7), which simplifies the construction of the amplifier chains that comprise the array. The linewidth of the lasers must consequently be less than 10 MHz, and with such narrow widths, nonlinear stimulated Brillion scattering limits the power of the units cells to a few hundred watts [3]. The end result is that the power record for a laser array is 5 x 150W = 750 W [4], which is disappointing compared to the current record for a single fiber, 10 kW [5].

Spectral beam combining. This technique [6] is espoused by researchers at Freidrich-Schiller University Jena and MIT Lincoln Labs. An array of high power fiber lasers, each operating at a slightly different wavelength, are combined by a dielectric-coated diffraction grating (the Jean and MIT gratings were both made by LLNL). The technique does not require active phase control, making it less complex than active phasing approaches, but it does require that the output beam from each laser be diffraction-limited. The record power is 1.1 kW [7].

Self-Fourier Cavities. In this technique, lasers are combined in a "self Fourier" cavity, which forces the field distribution of the array into one that is the Fourier transform of itself [8]. This technique does not require the individual lasers to be phase locked; rather, it is believed that the lasers organize themselves into the appropriate distribution to maximize the array's output power.

This technique remains interesting to the DOD community. Corcoran Engineering was recently awarded $5M from JTO to pursue modeling work (near term) and produce a prototype array of five lasers that combine to generate 750 kW, and an array of 21 low-power lasers to determine the scaling limits of the technique (long term).

Results to Date

Under LDRD funding, we have built four amplifier chains, each tuned in length to within 1 ps of each other; the amplifiers are fed and recombined by 1 x 4 fiber-based splitters. The seed for the development work has been a fiber-based mode-locked amplifier having a repetition rate of 40 MHz and bandwidth of 30 nm (pulse durations of 100 fs).

The lengths of the amplifiers have been tuned so that the system is capable of recombining pulses over the full bandwidth of source; moreover, full recombination (without spectral dropouts) lasts for tens of seconds, due the common-path architecture of the system.

The largest challenge overcome to date has been to measure the absolute path lengths of the amplifier chains to sub-picosecond levels. The method developed is to:

Step 1. Assemble amplifiers to equal lengths by precision cutting and splicing. This results in path lengths to within 2 cm (determined in Step 2).

Step 2. Measure the time of flight of the arms of the array to within 1 ps. The measurements are made using a network analyzer and narrowband source (in our case, a tunable laser, though tunability is not necessary). The RF output of the network analyzer drives an electro-optic modulator; the network analyzer's frequency is swept from 1 GHz to 1.5 GHz, and the analyzer measures the resulting sweep of the RF phase. The time of flight is the slope of the RF phase vs. RF frequency curve.

Step 3. Refine the match of the amplifier lengths by precision cutting of longer amplifiers; this results in lengths matched to less than 1 mm.

Step 4. Tune the lengths of the amplifiers by stretching a patch cable; this results in 0.1 ps matching, sufficient to cover a bandwidth of 30 nm.

Step 5. View the results on optical spectrum analyzer.

We have also demonstrated that we can stretch the pulses in time to 1 ns (using a chirped fiber Bragg grating), co-propagate an out of band CW signal with the pulses (a tunable laser), and separate the CW signal from the combined pulses at the output via a narrow-band filter.

The next step toward full phase locking the array is to impress individual ~ 100 MHz RF modulations onto the four amplifiers, thus allowing us to adapt the scheme developed by Shay and coworkers for locking CW sources to our pulsed source. This is the point we have currently reached.

In future work (see following section) we plan to stack pulses from a single pulsed fiber laser source inside a resonant cavity. For this, we do not need multiple 100 MHz RF modulators; instead, we only need to lock the resonant frequency of the laser source to the resonant frequency of the stacking cavity – adjusting one element rather than three, a significant simplification.

Future Work (Funded by Others)

We expect the co-phasing work to continue under separate funding, though in a simpler form. Instead of combining pulses from many amplifiers we would combine many sequential pulses from a single fiber laser via a resonant cavity. Such a scheme is less expensive to build and test (and eventually, to field), though significant technical hurdles must be overcome, including the development of a low-loss mechanism for releasing the energy that is built up within the cavity.

The work will be part of a joint effort with LBL, funded by UCOP, to seek a path to 10 mJ, 100 kHz sources to serve as pumps for short-pulse seeds for the FEL-based light source they are developing.

Summary

A primary result of the research has been the understanding that it is expensive, in terms of component costs and complexity, to scale pulse energy by scaling fiber count. This is because the most expensive pieces of each amplifier chain – the final amplifiers – need to be replicated for each of the unit cells of the array. While scaling from one laser to several can lead to significant benefits (adding one laser increases the energy by a factor of two), large counts leads to diminishing returns (the 101^{st} laser only increased the energy by 1%).

A second result is the development of techniques for adjusting and tuning the lengths of amplifier chains to sub-picosecond levels. These two results – understanding of scaling costs and length-tuning – played roles in our response to DARPA's recent call for beam-combining pulsed fiber lasers, for which we have been awarded $3M. Understanding scaling costs and complexity led to the realization that the large arrays espoused by others would not meet DARPA's needs (roughly 100 lasers would be required, each costing $40k). We instead proposed to combine 10 higher energy pulses via the Raman effect; since this method does not require the beams to be coherent, the unit cell energy can be relatively high (since nonlinear phase distortions do not affect them); thus only 10 lasers are needed. The winning technique does require that the lasers' lengths to be tuned to within 10 ps of each other; fortunately, we have already accomplished under the LDRD funding.

References

[1] T. M. Shay, V. Benham, J. T. Baker, B. Ward, A. D. Sanchez, M. A. Culpepper, D. Pilkington, J. Spring, D. J. Nelson, and C. A. Lu, "First experimental demonstration of self-synchronous locking of optical coherence by single-detector electronic-frequency tagging of fiber amplifiers" Proc. SPIE 6304, 63040W (2006).

[2] S. J. Augst, J. K. Ranka, T. Y. Fan, and A. Sanchez, "Beam combining of ytterbium fiber amplifiers (invited)," J. Opt. Soc. Am. B 24, 1707 – 1715 (2007).

[3] M. Hildebrandt, S. Buesche, P. Weels, M. Frede, and D. Kracht, "Brillouin scattering spectra in high-power single-frequency ytterbium doped fiber amplifiers," Opt. Express 16, 15970-15979 (2008).

[4] T. M. Shay, J. T. Baker, A. D. Sancheza, C. A. Robin, C. L. Vergien, A. Flores, C. Zerinque, D. Gallant, C. A. Lu, B. Pulford, T. J. Bronder, and A. Lucero, "Phasing of High Power Fiber Amplifier Arrays," in Advanced Solid-State Photonics, OSA Technical Digest Series (CD) (Optical Society of America, 2010), paper AMA1.

[5] Gapontsev, V. P., "New Milestones in the development of super high power fiber lasers," presented at Photonics West, OE/LASE 2006, San Jose CA, Jan 21-26 (2006).

[6] S. Klingebiel, F. Röser, B. Ortaç, J. Limpert, and A. Tünnermann, "Spectral beam combining of Yb-doped fiber lasers with high efficiency," J. Opt. Soc. Am. B 24, 1716-1720 (2007).

[7] O. Schmidt, C. Wirth, I. Tsybin, T. Schreiber, R. Eberhardt, J. Limpert, and A. Tünnermann, "Average power of 1.1 kW from spectrally combined, fiber-amplified, nanosecond-pulsed sources," Opt. Lett. 34, 1567-1569.

[8] C. J. Corcoran, F. Durville, "Experimental demonstration of a phase-locked laser array using a self-Fourier cavity," App. Phys. Lett 86, 201118 (2005).